ontario hydro
research division

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research
Reproduced in Whole or in Part

To: DR. D. MILLS
Director
Research Division

CONDUCTORS FOR OVERHEAD TRANSMISSION – BENEFITS OF USING COMPACT, LOW-LOSS, AND LARGER DIAMETER CONDUCTORS

J.S. Barrett and M.A. Green

Electrical Research Department

Abstract

The cost of building and operating overhead transmission lines is governed by the choice of conductor. Selecting a larger conductor will increase the capital cost of a line, but decrease the resistive energy losses and the need for generating facilities to provide the lost energy. Simple economic analyses are used in this report to demonstrate the potential for very substantial savings through the use of larger and more carefully designed conductors. Use of Compact ACSR conductors in place of Conventional "round-wire" ACSR, for all future upgrading and new construction projects, could yield savings in excess of $400 million. The benefits of Low-Loss conductors, designed with methods developed in the Research Division, could exceed $40 million; while the use of larger diameter conductors in new construction and a long term replacement program, to shift the balance between losses and capital line costs, could save a further $500 million.

1. INTRODUCTION

The economics of overhead transmission lines are governed by three major factors

- the capital cost of the lines
- the cost of resistive energy losses in the lines over their lifetime
- the capital cost of generating facilities required to provide the lost energy

job	file	date	report no.
10-501-031	812.2	June 23, 1988	88-166-K

89-02544/

LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights, or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

In each case, "cost" refers to the present value of the indicated item. Optimum economic benefit of a transmission line is achieved by striking a strategic balance between the line costs and the two components of the loss costs. For the present Ontario Hydro transmission system, the present value of energy losses and extra generating facilities is about **60 percent greater** than the present value of the transmission lines. Shifting the strategic balance in the direction of lower losses can thus potentially result in very substantial savings.

Three initiatives for improving the economic benefit of both existing and future transmission lines are proposed and evaluated in this report. When uprating existing lines and when building new lines, the choice of conductor has a dominant influence on both the capital line cost and the magnitude of the losses. We exploit that influence, and focus on the benefits that can be gained through the use of superior conductor designs and larger diameter conductors.

The first proposed initiative involves switching from **Conventional** round-wire conductors to **Compact** conductors [1] with trapezoidal aluminum wires. For existing transmission lines, we estimate the benefits that can be expected if all Conventional conductors are replaced (over a 50 year period as part of the normal maintenance and upgrading program) with Compact conductors. Potential cost savings for future transmission lines are also calculated. Again, the options being compared are continued use of Conventional conductors versus a complete shift to Compact conductors.

The second proposal is to use new **Low-Loss** conductors developed in the Research Division. These conductors are carefully designed to have lower resistance without increasing the amount of material. Low-Loss conductors can reduce the cost of transmission energy losses with only a very minor increase in capital line costs. The benefits for both a 50 year upgrading program and for new construction are evaluated.

Our final proposal is to optimize the balance between line costs and loss costs by using larger conductors in the future. Use of a larger conductor will increase the cost of the lines but will decrease the cost of losses and the extra generating facilities. Simple calculations are used to demonstrate the relationship between the average size of existing conductors and the average size which would yield the lowest total transmission cost. Estimates are obtained of the potential benefits of using conductors as much as 80 percent larger than the current mean.

The recommended actions should permit realization of the more than $1 billion of identified potential benefits. To be fair, we must acknowledge that design and planning strategies have been changing in response to an evolving world economy. There has been a trend in recent years toward the use of larger conductors and of Compact conductors, so not all of the claimed benefits will be new. However, we believe that the larger portion of the projected benefits can only be realized through deliberate and comprehensive changes in the strategic balance between capital investment in transmission lines and the long term cost of losses.

The dollar and percentage figures used below are for illustration purposes only, and are subject to change depending on Corporate financial strategy. Similarly, the calculation methods are a vast simplification of what one would apply in a detailed valuation. We have, however, attempted to be realistic yet conservative in all estimates of potential savings.

Where possible, numbers have been drawn from reliable sources [2-5]. The true savings that may be achievable are unlikely to be less than 50 percent of what we claim below, nor more than 200 percent of our calculated values.

2. CONDUCTORS FOR OVERHEAD TRANSMISSION

Research projects carried out over the past five years have led to a new understanding of the performance and economics of conductors used on overhead transmission lines.

These conductors are generically known as Aluminum Conductor Steel Reinforced (ACSR). They consist of several concentric layers of helically wound wires, with successive layers wound in opposite directions (Figure 1). The inner layers are made of steel wires to provide the required tensile strength, while the outer layers are aluminum to minimize the conductor's electrical resistance. The ratio of steel to aluminum can be adjusted to achieve the desired balance between strength and conduction. The cross-sectional area of aluminum controls the conductor's resistance.

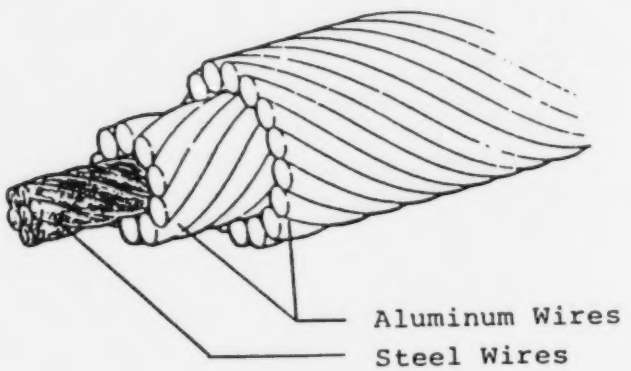

Figure 1: Aluminum Conductor Steel Reinforced (ACSR)

2.1. Conventional ACSR

The aluminum and steel layers of **Conventional** ACSR conductors are made from round wire strands. The diameters of the wires in each of the steel layers of a conductor are equal, and the diameters of the wires in each of the aluminum layers are equal. (The steel wires are, however, typically smaller than the aluminum wires.) The **lay lengths** of the wires in the various layers (that is the length of conductor in which an individual wire wraps around 360°) are normally kept within a range that is easy to manufacture while also providing a mechanically-stable conductor structure.

2.2. Compact ACSR

Compact ACSR conductors are similar to Conventional ACSR conductors, but with one major difference. The aluminum layers are built from trapezoidal wires, which fit together snugly to form a conductor with less empty space. This has the advantage of packing 20 percent more aluminum into a conductor without increasing its diameter. Figure 2 illustrates the cross-sections of Conventional and Compact ACSR conductors.

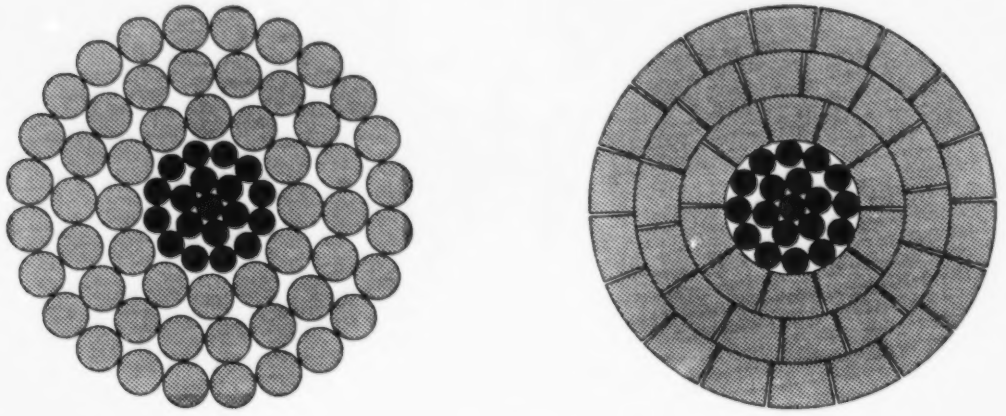

Figure 2: Cross-sections of Conventional and Compact ACSR conductors of the same diameter

2.3. Low-Loss "Optimized" ACSR

It has long been known that ac current in ACSR conductors is not uniformly distributed through the aluminum layers. The consequence is that the effective resistance of a transmission line is greater than one would calculate using only the resistivity of aluminum and the conductor dimensions. An experimental and theoretical study carried out in the Research Division has led to the first accurate model [6] of the electromagnetic behaviour of ACSR conductors. We have

- demonstrated that the current distribution within a conductor is significantly different from what had been previously claimed
- developed an analytical model, and corresponding software tools, to accurately predict the current distribution and ac resistance of any ACSR (or similar) conductor

- developed methods [7] to design ACSR conductors with ac resistance reduced by 2 to 5 percent from standard Compact and Conventional ACSR
- demonstrated a 4 percent reduction in ac resistance of an ACSR conductor (grackle) widely used in the Hydro system [7]
- obtained a U.S. patent (and applied for Canadian patent) for ACSR conductors designed to have reduced ac resistance

These new **Low-Loss "optimized"** ACSR conductors provide lower ac resistance and hence lower energy losses than standard ACSR conductors with the same aluminum and steel areas. The improved performance is achieved by recognizing that the current actually flows along the spiral paths of the component wires, and that the various layers act like the windings of a transformer. A uniform current distribution, and minimal magnetic losses, are then obtained by providing similar wire area for circulation of current in the clockwise and counterclockwise directions.

Low-Loss designs can be developed for both Conventional and Compact ACSR, as well as for new hybrid structures which incorporate a combination of compact and round-wire aluminum layers. Designs can balance the current distribution through minor modification of lay lengths or through the use of different size wires in different layers. Sufficient flexibility is available to tailor mechanical characteristics to meet a wide range of requirements. Figure 3 illustrates some of the possible Low-Loss designs.

3. BENEFITS OF COMPACT ACSR

3.1. Reduced Resistance

The chief benefit of Compact ACSR derives from its reduced resistance/diameter ratio relative to Conventional ACSR. Given a Compact and a Conventional ACSR conductor of the same diameter, the Compact conductor will typically have 20 percent less resistance. The Compact conductor would not require stronger towers, however, because the limiting load factor on towers is generally the transverse load from wind on the conductor – and that is proportional to the conductor diameter.

The 20 percent reduction in resistance comes from three sources. For a given diameter, the greater amount of aluminum in a Compact conductor gives a 17 percent reduction in resistance. Two percent comes from more uniform current distribution, and the final one percent comes from reduced operating temperatures, due to better thermal conduction from the inner layers to the outer layers.

3.2. Increased Conductor Cost

If we continue the comparison of Compact ACSR with Conventional ACSR of the same diameter, we also find some increased costs. The Compact conductor has 20 percent more aluminum, so there is the extra material cost. There is also a slight increase in the manufacturing cost, making the conductor an additional 1 - 2 percent more expensive.

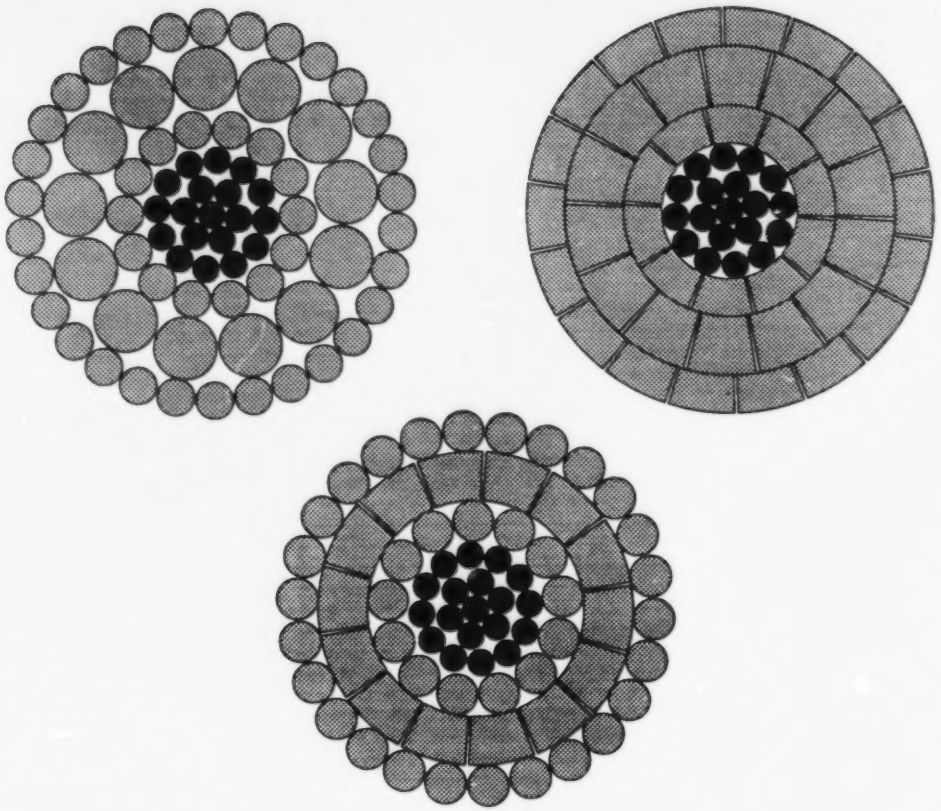

Figure 3: Some Low-Loss conductor designs

While the transverse wind loads on the Compact and Conventional conductors will be similar, the vertical load on the towers will increase for Compact conductors in proportion to the amount of material. In some isolated cases the towers or line hardware may require strengthening to carry this additional load.

3.3. Benefits for System Uprating

The design lifetime of a transmission line is typically 50 years. Many of the lines in the Hydro system are actually older than that, while many others can only be operated in a restricted fashion due to insufficient ground clearance at high temperatures. Over 90 percent of the existing transmission lines have Conventional round-wire ACSR conductors.

Several options are available for rejuvenating older lines, very often involving strengthening the towers and replacing the conductor with a larger conductor strung at higher tension. In any uprating project, substantial savings can be achieved if a Compact conductor

design is selected for the replacement conductor.

We evaluate the benefits of Compact ACSR in an uprating program on the following basis

- It is assumed that the normal maintenance and upgrading program would result in 2 percent of the conductors on the existing system being replaced each year for the next 50 years.
- Resistive losses in overhead transmission lines amount to 4 percent of system load. This percentage will not change significantly for existing lines, even when they are upgraded, since the trend is to operate lines "hot".
- The incremental cost of energy in 1988 is $20 per megawatt-hour. This cost does not include the capital cost of generating facilities required to supply that energy.
- The replacement value of the existing transmission system, excluding land, is $2,500 M. (See section 5.2.) The conductors account for 25 percent of this value.
- The replacement value of all existing generating facilities is $40,000 M. (See section 5.2.)
- The difference between the long term discount rate and the long term escalation rate in the cost of energy is 3 percent.
- The long term effective interest rate (discount rate - general escalation rate) will remain constant at 6 percent.

Given these assumptions, we evaluate the benefit of using **Compact ACSR** for all replacement conductors rather than **Conventional ACSR** of the same **diameter** – whatever that diameter might be. Due to the significant uncertainties in many of the numbers, rounding is used liberally to keep the numbers simple.

3.3.1. *Energy Savings.* Use of Compact conductors in a replacement program, as described above, would reduce electrical losses. The present value of saved energy is given by

$$\sum_{n=1}^{50} \frac{n}{50}\, 0.97^{n-1} \times 0.2 \times 0.04 \times 125{,}000{,}000\,\text{MWh} \times \$20/\text{MWh} \;=\; \$200\,\text{M}$$

where the factors	are for the
1/50	fraction of transmission lines replaced annaully
0.97 = (1. – .03)	yearly present value factor
0.2	20% reduction in losses
0.04	fraction of total energy lost in transmission
125,000,000 MWh	total annual energy generated
$20/MWh	incremental energy cost

3.3.2. *Avoided Generation Construction.* The reduction in line losses will reduce the need for new generating facilities to meet future demand. The present value of the avoided generation construction costs is

$$\sum_{n=1}^{50} \frac{1}{50}\, 0.94^{n-1} \times 0.2 \times 0.04 \times \$40{,}000\,\text{M} \;=\; \$100\,\text{M}$$

where the factors are for the

0.94 = (1. – .06)	yearly present value factor for line construction
$40,000 M	value of present generating facilities

3.3.3. *Additional Conductor Cost.* The additional aluminum and increased manufacturing costs for the Compact conductors are not insignificant. The estimated present value of the increased cost relative to using Conventional conductors is

$$\sum_{n=1}^{50} \frac{1}{50}\, 0.94^{n-1} \times 0.22 \times 0.25 \times \$2{,}500\,\text{M} \;=\; \$44\,\text{M}$$

3.3.4. *Summary.* The following table summarizes the benefits of using Compact ACSR rather than Conventional ACSR in a long term conductor replacement program.

Avoided energy losses	$200 M
Avoided generation construction	$100 M
Additional conductor cost	($44 M)
NET BENEFIT	$256 M

This estimate of net benefit is believed to be quite conservative. For example, the true cost of doubling our present generation capacity is probably much greater than the assumed $40,000 M replacement value of the present facilities.

Also, the calculations assume that the present transmission system losses are uniformly distributed. This is clearly not the case – some lines are much more heavily loaded than others. A well-planned upgrading program would see the more lossy conductors replaced first, resulting in true energy savings much greater than $200 M. Speeding up the entire replacement program, from 50 years to perhaps 25 years, would again increase the energy savings – but at some additional expense due to retrofitting of lines which have not yet reached their design lifetime.

3.4. Benefits for New Construction

In the design of new transmission lines there is greater potential for optimization of the conductor size than is possible with upgrading projects. This is because there is no constraint posed by existing towers. We shall suppose that the conductor size will be chosen to provide the optimum balance between capital line cost and the present value of the cost of losses and generation required to provide those losses over the life of the line.

We compare below the relative benefit of using **optimally selected** Conventional ACSR conductors on new lines with using Compact ACSR conductors on the same lines. It is quite easy to show that it is much more economical to use a Compact conductor of the same **diameter** as a given Conventional ACSR conductor than a Compact conductor of the same **area**. So, to be definite, our comparison will again be between the use of Conventional and Compact ACSR conductors of the same diameter.

A modest number of assumptions are again necessary in order to permit a projection of the benefits of using Compact ACSR in place of Conventional ACSR. In all cases we have attempted to be conservative. The following items provide the basis for our calculations.

- It is assumed that system load will grow at 2 percent per year for the next 50 years. New transmission facilities will be required to carry that power.
- The losses in new transmission lines will average 3 percent, rather than the 4 percent in the present system. The reduction is due to anticipated increases in conductor size as a result of more careful economic optimization, and due to higher average line voltage.
- Escalation and inflation rates will be as discussed above, in the evaluation of benefits for system uprating.
- The replacement values of the existing transmission and generation facilities are as discussed above, in the evaluation of benefits for system uprating.

The following paragraphs itemize the benefits of Compact over Conventional ACSR in new construction projects over the next 50 years.

3.4.1. *Energy Savings.* The present value of saved energy due to lower resistance of new lines built with Compact ACSR is

$$\sum_{n=1}^{50} \left[(1.02)^{n-1} - 1\right] (0.97)^{n-1} \times 0.2 \times 0.03 \times 125{,}000{,}000\,\text{MWh} \times \$20/\text{MWh} \;=\; \$193\,\text{M}$$

3.4.2. *Avoided Generation Construction.* Reduced line losses due to use of Compact ACSR will reduce also the need for new generation capacity. The present value of avoided generation capital costs is

$$\sum_{n=1}^{50} \left[\frac{1}{50}(1.02)^{n-1}\right] (0.94)^{n-1} \times 0.2 \times 0.03 \times \$40{,}000\,\text{M} \;=\; \$102\,\text{M}$$

3.4.3. *Additional Conductor Cost.* The present value of projected additional cost for aluminum and conductor manufacturing is

$$\sum_{n=1}^{50} \left[\frac{1}{50}(1.02)^{n-1}\right] (0.94)^{n-1} \times 0.22 \times 0.25 \times 1.3 \times \$2{,}500\,\text{M} \;=\; \$76\,\text{M}$$

The factor of 1.3 is to compensate for the larger conductor size or line voltage necessary to reduce average losses to 3 percent.

3.4.4. *Summary.* The following table summarizes the benefits of using Compact ACSR rather than Conventional ACSR (of the same aluminum area) in new construction over the next 50 years.

Avoided energy losses	$193 M
Avoided generation construction	$102 M
Additional conductor cost	($76 M)
NET BENEFIT	$219 M

It is very important to note that these benefits have been calculated on the assumption that the optimum size conductors will be chosen for new lines. They also assume **a reduction in average losses on new lines from 4 percent to 3 percent**. The present value of that saving is not included in the benefits calculated above. (See section 5.)

4. BENEFITS OF LOW-LOSS "OPTIMIZED" CONDUCTORS

We shall assume, for purposes of calculating the economic benefits created by Low-Loss conductors, system uprating and expansion programs exactly as described above in the discussion of Compact conductors. The benefits calculated below will then be the incremental benefit of using Low-Loss designs, which is **in addition to** the benefits of using Compact conductors in those programs.

4.1. Reduced Resistance

As we have discussed above, conductors designed using the methods developed in the Research Division have lower resistance than standard ACSR conductors. The ac resistance of Conventional ACSR conductors is typically reduced by 3 to 5 percent. Compact conductors, being somewhat better to begin with, can have their resistance reduced by about 2 percent.

This improvement is achieved without changing the amount of material involved. Thus any additional cost will be due to a slight increase in manufacturing costs.

4.2. Improved Mechanical Performance

The flexibility in conductor design permitted by the use of layers of differing thickness allows conductors to be constructed to meet a wide range of mechanical requirements. For example, it is possible to design a Low-Loss conductor which will not twist under tension. Such a low-torque conductor should be easier for construction crews to string, and may also be less costly to maintain.

Again, due to the wide range of conductor design options, Low-Loss conductors can be used without requiring **any** change to other aspects of line design (towers, insulators, hardware, ...).

4.3. Benefits for System Uprating

The additional benefit of using Low-Loss conductor designs in the assumed uprating program is calculated in exactly the same fashion as the initial benefits of using Compact conductors.

4.3.1. *Energy savings.* The present value of saved energy due to the 2 percent lower resistance of **Low-Loss** Compact conductors is

$$\sum_{n=1}^{50} \frac{n}{50} (0.97)^{n-1} \times 0.02 \times 0.8 \times 0.04 \times 125{,}000{,}000\,\text{MWh} \times \$20/\text{MWh} = \$16\,\text{M}$$

The factor of 0.8 allows for the 20 percent reduction in resistance already achieved through the use of Compact conductors.

4.3.2. *Avoided Generation Construction.* The reduction in line losses will reduce the need for new generation facilities to meet future demand. The present value of the avoided generation construction costs is

$$\sum_{n=1}^{50} \frac{1}{50} (0.94)^{n-1} \times 0.02 \times 0.8 \times 0.04 \times \$40{,}000\,\text{M} = \$8\,\text{M}$$

4.3.3. *Additional Conductor Cost.* We assume a 1 percent premium on the cost of the Low-Loss conductors. The present value of the additional cost, above the cost of Compact ACSR, is

$$\sum_{n=1}^{50} \frac{1}{50} (0.94)^{n-1} \times 0.01 \times 0.25 \times \$2{,}500\,\text{M} = \$2\,\text{M}$$

4.3.4. *Summary.* The following table summarizes the benefits of using **Low-Loss** Compact ACSR rather than **standard** Compact ACSR in a long term conductor replacement program.

Avoided energy losses	\$16 M
Avoided generation construction	\$8 M
Additional conductor cost	(\$2 M)
NET BENEFIT	\$22 M

4.4. Benefits for New Construction

The calculation of additional benefits from using Low-Loss conductor designs in future transmission line construction follows the similar calculations for use of Compact conductors. We again assume a 1 percent premium on the manufacturing cost of Low-Loss conductors, and compute only the incremental savings which are in addition to the savings calculated above for use of Compact ACSR.

4.4.1. *Energy Savings.* The present value of saved energy due to 2 percent lower resistance of Low-Loss conductors is estimated at

$$\sum_{n=1}^{50}\left[(1.02)^{n-1}-1\right](0.97)^{n-1}\times 0.02\times 0.8\times 0.03\times 125{,}000{,}000\,\text{MWh}\times \$20/\text{MWh} \;=\; \$15\,\text{M}$$

4.4.2. *Avoided Generation Construction.* The present value of avoided generation capital costs due to the use of Low-Loss conductors is

$$\sum_{n=1}^{50}\left[\frac{1}{50}(1.02)^{n-1}\right](0.94)^{n-1}\times 0.02\times 0.8\times 0.03\times \$40{,}000\,\text{M} \;=\; \$8\,\text{M}$$

4.4.3. *Additional Conductor Cost.* The present value of projected additional cost for aluminum and conductor manufacturing is

$$\sum_{n=1}^{50}\left[\frac{1}{50}(1.02)^{n-1}\right](0.94)^{n-1}\times 0.01\times 0.25\times 1.3\times \$2{,}500\,\text{M} \;=\; \$3\,\text{M}$$

4.4.4. *Summary.* The following table summarizes the present value of benefits from using **Low-Loss** Compact ACSR in new construction over the next 50 years.

Avoided energy losses	$15 M
Avoided generation construction	$8 M
Additional conductor cost	($3 M)
NET BENEFIT	$20 M

4.4.5. *Comments.* The benefits of using Low-Loss designs would be greater by about a factor of 2 for Conventional round-wire ACSR conductors. Similarly, if the average loss in the transmission system is not reduced from 4 percent to 3 percent then the benefits of Low-Loss conductors would again be increased by a factor of 1.4 (for new construction). This last number is greater than the 4/3 ratio because the benefits of Low-Loss designs are greater at higher currents.

A development and testing program is still required for Low-Loss conductors to provide direction in the adoption of a reasonable number of "standard" designs, and to build confidence in the field. Additional revenue can potentially be gained by licensing production of Low-Loss conductors in the USA and Canada (assuming a Canadian patent is awarded).

Work is proceeding on the development of "user friendly" software to facilitate the design and evaluation of all kinds of ACSR conductors, including Low-Loss designs.

5. SELECTING THE BEST CONDUCTOR SIZE

The issue of selecting the optimum conductor size to maximize the economic benefit of transmission facilities has been broached several times above. The comment was made in the introduction that the present value of the cost of losses (including associated generating facilities) is 60 percent greater than the value of the entire transmission system. We will elaborate briefly, here, with some very simple calculations that can provide guidance for future strategies.

5.1. Cost of Losses

The calculations presented above were based on 4 percent of energy leaving generating facilities being lost as heat from the transmission lines. This number is derived from the 1985 Statistical Yearbook. Total energy generated is about 125 million MWh, and the incremental cost of energy is about $20 per MWh. Combining these numbers with the 3 percent difference between discount and escalation rates for the cost of energy allows us to compute the present value of energy losses expected to be incurred on the present transmission facilities over the next 50 years:

$$\sum_{n=1}^{50} \frac{n}{50} (1-.03)^{n-1} \times 0.04 \times 125{,}000{,}000\,\text{MWh} \times \$20/\text{MWh} \;=\; \$2{,}600\,\text{M}$$

Four percent of the existing generating facilities are required solely to provide the power for those losses. A very rough estimate of the true value of existing generating facilities is obtained by considering the cost of Darlington to be $10,000 M, and scaling that number up by a factor of 4 to "evaluate" the Pickering A and B and Bruce A and B stations. The remainder of the generating facilities are then ignored. On this basis the value of the generating facilities required to provide the energy lost from transmission lines is

$$0.04 \times \$40{,}000\,\text{M} \;=\; \$1{,}600\,\text{M}$$

In round numbers, the total present value of the cost of losses and the facilities required to provide those losses is $4,000 M.

5.2. Value of Existing Transmission System

For the existing transmission system, we are interested in again in the true replacement value of existing lines – our objective is not to examine the quality of past decisions but instead to guide future decisions. Since detailed numbers are not available, the following estimate must be considered as only a very rough approximation. Nevertheless, it is probably not more than 20 percent in error.

If we consider all voltage classes there are a total of 27,000 circuit kilometers of transmission lines. We shall assume that that is equivalent to 12500 kilometers of double-circuit 230 kV lines. The dominant voltage class is 230 kV, and the cost of a double-circuit 230 kV line is approximately $200 K per kilometer. That puts the total value of the Ontario Hydro transmission system at $12500 \times \$0.2\,\text{M} \;=\; \$2{,}500\,\text{M}$.

5.3. Determining the Best Balance

If the cost of losses and the cost of transmission lines can be related to the size of conductor used on the transmission lines, then one should be able to determine the conductor size which yields the lowest overall cost for the Corporation. We make the following two assumptions

- The cost of losses varies inversely with the conductor area
- One half of the capital cost of new lines is fixed, and one half grows linearly with conductor area.

We use the values of facilities and losses calculated above for the present Hydro system as a reference point. Let us call the average conductor area on our existing transmission lines A_o. The scaling rules stated above then imply that if the conductor area were changed to a new value A then the total cost of the transmission system would be

$$C = (0.5 + 0.5 \times \frac{A}{A_o}) \times \$2{,}500\,M + \frac{A_o}{A} \times \$4{,}000\,M$$

This cost, C, is lowest when $A = 1.8 \times A_o$, indicating that A_o is smaller than optimal. Substituting the optimal conductor size back into the cost formula gives C = $5,722 M, a **reduction of $778 M** from the cost with the actual present conductor size A_o.

The conclusion from this simple calculation is that an optimal balance between losses and capital line costs will be achieved only if larger conductors – perhaps 80 percent larger – are used in the future, when uprating existing lines and on new construction projects.

5.4. Potential Savings

The $778 M estimate does not actually represent "savings", since it is clearly not possible to transform the existing system into one which has 80 percent larger conductors. However, real savings should result if an attempt is made to reduce the total losses from 4 percent to something closer to 4 / 1.8 = 2.2 percent in the long term.

Real benefits can be achieved by using larger size conductors both when uprating existing lines and when building new transmission lines. This applies to all voltage classes, but the greatest gains are expected at the lower voltages. A very rough estimate of the present value of the potential real savings is $500 M.

6. CONCLUSION AND RECOMMENDATIONS

We have demonstrated, through simple economic analyses, that the use of Compact ACSR conductors and the use of new design methods for reducing the ac resistance of conductors would yield substantial economic benefits. We have also presented a very simple analysis which indicates that larger conductors should be used in order to minimize the long term cost of transmission lines.

The identified potential benefits are summarized below.

ACTION	BENEFIT
Use of Compact ACSR	
- system uprating	$256 M
- new construction	$219 M
Use of Low-Loss Designs	
- system uprating	$22 M
- new construction	$20 M
Use of Larger Conductors	$500 M
TOTAL BENEFIT	$1017 M

In terms that may be more meaningful, this benefit corresponds to an improvement in the long term overall efficiency of Ontario Hydro of about 1 percent.

Some of these benefits will already be realized through continuation of present design and planning trends toward increased use of Compact and larger diameter conductors. Clear strategy decisions are required, however, in order to create for the future the most economical transmission system possible.

To achieve the identified benefits, we recommend the following

- Use **Compact** ACSR conductors for all overhead transmission lines, both in upgrading projects and in new construction at all voltage levels. Discontinue use of Conventional ACSR.
- Specify, for all conductors, **Low-Loss** designs, using design methods developed in the Research Division.
- Increase the effort to develop planning and design tools for economic optimization of transmission lines. Use those tools to determine the most economical conductor size for future upgrading and new construction projects.

The Low-Loss conductors invented at Research have been patented in the USA, and a Canadian patent is being sought. Widespread availability of Low-Loss conductors would benefit Ontario Hydro and the entire electric utility industry. To assure their future, we believe that Hydro should

- Develop and license the manufacture of **Low-Loss** ACSR in Canada and the USA.

Finally, although all of the above discussions have focused on conductors for use on transmission lines, the potential benefit of different conductors on the distribution system should also be contemplated. Distribution losses also consume 4 percent of the total energy generated. We therefore recommend that Hydro

- Investigate the benefit of using Compact, Low-Loss, and larger diameter conductors in the distribution system.

Approved by:

A.F. Baljet
Manager
Electrical Research Department

Prepared by:

J.S. Barrett
Physicist
Transmission and Special Projects Section
Electrical Research Department

M.A. Green
Physicist
Transmission and Special Projects Section
Electrical Research Department

REFERENCES

[1] McCulloch, A.R. and P. Ralston, "Compact Conductors for Transmission Lines", CIGRE S.C. 22 Symposium, Stockholm, June 1981.

[2] Ontario Hydro, "Ontario Hydro Statistical Yearbook: Supplement to the Annual Report", 1985.

[3] Economics & Forecasts Division, "Cost Escalators, Spring Review", File 706.01 (#269), May 1988.

[4] System Planning Division, "Meeting Future Energy Needs, Draft Demand/Supply Planning Strategy", Report 666SP, December 1987.

[5] Communications Research Section, Corporate Relations Branch, "Inside Hydro", July 1987.

[6] Barrett, J.S., Nigol, O., Fehervari, C.J., and Findlay, R.D., **A New Model of ac Resistance in ACSR Conductors**, IEEE Trans., Vol. PWRD-1, No. 2, April 1986, pp 198-208.

[7] Barrett, J.S., **Optimization of Conductor Design**, IEEE Winter Power Meeting, Paper Number 88 WM 067-1, February 5, 1988.